Phase Lags in the Optical-Infrared Light Curves of AGB Stars

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ABSTRACT

To search for phase lags in the optical-infrared light curves of asymptotic giant branch stars, we have compared infrared data from the COBE DIRBE satellite with optical light curves from the AAVSO and other sources. We found 17 examples of phase lags in the time of maximum in the infrared vs. that in the optical, and 4 stars with no observed lags. There is a clear difference between the Mira variables and the semi-regulars in the sample, with the maximum in the optical preceding that in the near-infrared in the Miras, while in most of the semi-regulars no lags are observed. Comparison to published theoretical models indicates that the phase lags in the Miras are due to strong titanium oxide absorption in the visual at stellar maximum, and suggests that Miras pulsate in the fundamental mode, while at least some semi-regulars are first overtone pulsators. There is a clear optical-near-infrared phase lag in the carbon-rich Mira V CrB; this is likely due to C_2 and CN absorption variations in the optical.

Subject headings: infrared: stars— stars: AGB and post-AGB— stars: variable

1. Introduction

Low mass stars (<8 M$_\odot$) are destined to pass through the Asymptotic Giant Branch (AGB) evolutionary stage. AGB stars are characterized by physical pulsations and variations in the emitted light (Wood 1997; Olofsson et al. 1999), with high mass loss rates near the end of the AGB stage (Knapp & Morris 1985). Dynamical models show that this mass loss is driven by the pulsations, combined with non-LTE radiative relaxation and radiative acceleration of dust (Bowen 1988; Bowen & Willson 1991; Willson 2000). Since these stars contribute significantly to the enrichment of the interstellar medium (Busso, Gallino, & Wasser-burg 1999), the study of AGB stars is vital to understanding the lifecycle of the Galaxy as a whole.

To better understand the structure and evolution of AGB stars, simultaneous optical and infrared monitoring can be useful. Since 1933, it has been known that the maximum of the light curves for Mira variables in the near-infrared tends to lag that in the optical by about 10% of the pulsation period (Petit & Nicholson 1933; Lockwood & Wing 1971; Barnes 1973; Maran 1977; Kerschbaum, Lebzelter, & Lazaro 2001; Smith et al. 2002; Smith 2003; Pardo et al. 2004). These phase lags are still not well-quantified, and only a few examples have been studied in detail.

With the advent of the Diffuse Infrared Background Experiment (DIRBE) (Hauser et al. 1998) instrument on the Cosmic Background Explorer (COBE) satellite (Boggess et al. 1992), many high quality infrared light curves for AGB stars became available (Smith et al. 2002; Smith 2003; Knapp et al. 2003). The DIRBE instrument provided photometry in 10 broadband infrared filters (1.25, 2.2, 3.5, 4.9, 12, 25, 60, 100, 140, and 240 μm) with good temporal coverage ($100 - 1000$ data points in a 10 month period). This database was used to construct the COBE DIRBE Point Source Catalog (Smith, Price, & Baker 2004), in which DIRBE photometry for essentially all of the infrared-bright unconfused stars are tabulated and information on their DIRBE variability is provided. These light curves have been filtered to remove data points affected by nearby companions, and stars with companions in the DIRBE beam have been flagged and information about the companion is provided. In previous studies using DIRBE data, a few examples of optical to near-infrared phase lags have been found (Smith et al. 2002; Smith 2003; Pardo et al. 2004). In a few cases, offsets between the near-infrared and mid-infrared maxima were also found (Smith et al. 2002; Smith 2003). In the current project, we expand these studies to a larger sample.

2. Method

We pared down the 11,788 sources in the COBE DIRBE catalog (Smith, Price, & Baker 2004) to the 290 stars with DIRBE amplitudes (Δmag) greater than 5 times the uncertainty in the amplitude at any of the five shortest wavelength bands, that were unflagged at that wavelength. We compared the light curves from these stars with the visible curves from the American Association of Variable Star Observers (AAVSO[1]). Of these stars, 199 were in the AAVSO database, 172 with AAVSO measurements for the time period in $1989 - 1990$ that DIRBE was operational at cryogenic temperatures (JD $= 2447874 - 2448154$) (Hauser et al. 1998). High quality visual light curves for RX Lep and UX Dra were available for this time from Percy, Wilson, & Henry (2001) and Buchler, Kolláth, & Cadmus (2004), respectively; for these stars, these light curves were used instead

of AAVSO data. We also searched the Hipparcos database (ESA 1997) for optical data for the same time period, but found no new examples of phase lags.

3. Phase Lags

The visible - infrared light curves for many of the 172 stars in our sample indicate possible phase lags. Unfortunately, the results for most of these stars were ambiguous, either because their light curves are incomplete or are confused with contamination from nearby sources. However, 17 of the stars have sufficient data to clearly show optical-infrared phase effects while another 4 are sufficiently well defined that we concluded that they exhibit no phase effects. In sources which were flagged at a wavelength in the DIRBE Point Source Catalog, we carefully inspected the light curve and the DIRBE catalog confusion notes on the companion, and only included wavelengths where the effect of the companion was negligible.

The 21 sources in our final sample are listed in Table 1 in R.A. order, and their light curves are plotted in Figures $1 - 6$. Table 1 contains the variability type and period from the General Catalog of Variable Stars ((GCVS); Kholopov et al. (1985-1988)), and whether the star is carbon-rich, oxygen-rich, or with a carbon/oxygen ratio C/0 $\approx$ 1 (type 'S' stars). Table 1 also includes periods determined from the optical data for the 1200 day time period JD $= 2447500 - 2448700$, which overlaps with the DIRBE cryogenic period.

Note that the shape of the light curves in the optical and the infrared often differ significantly, with the infrared light curves tending to be more symmetrical than those in the optical. As seen in Figure 1, many of the light curves are incomplete and often a full pulsation period is not covered during the DIRBE mission. These properties limit the accuracy of the phase lag determinations. We used two independent methods to determine the lags. First, we determined the times of maxima by calculating running weekly averages for the light curves. We estimated the uncertainty on these maxima from the dates at which the brightness in the weekly-averaged light curve has decreased from maximum by 1σ, where 1σ is the rms in the original light curve during the week of maximum. Second, we estimated lags from cross-correlating

the light curves at the different wavelengths, after using a cubic spline to re-grid the data to regular 1 day intervals. In the cross-correlation, we only included data points brighter than the mean brightness, since the shapes of the light curves are not consistent from wavelength to wavelength. Table 1 shows that the phase lags measured using these two methods are consistent.

There is a clear difference between the Miras and the semi-regulars in Table 1. All 16 of the Miras in Table 1 have lags in which the optical maximum precedes that in the infrared, with offsets of $20 - \geq 90$ days. Of the 5 semi-regulars, four have no observed lags. The fifth semi-regular, L_2 Pup (Figure 3), has no lag or a possible reverse lag (near-infrared leading optical) for one maximum, and either a near-infrared/optical lag for the second maximum, or an extra optical maximum not seen in the near-infrared. In addition, the mid- and near-infrared light curves of L_2 Pup show striking differences in shapes.

The sole carbon-rich Mira in Table 1, V CrB, has a phase lag similar to those of the oxygen-rich Miras. The two S type (C/O ratio ~ 1) Miras R And and S Cas also have consistent lags. The sole carbon-rich semi-regular, UX Dra, shows no lag. There is also no clear distinction between the phase lags of stars with silicate emission features and those with featureless mid-infrared spectra, as indicated by the infrared spectral types from the Infrared Astronomical Satellite (IRAS) and the Infrared Space Observatory (ISO) (Kwok, Volk, & Bidelman 1997; Kraemer et al. 2002). Note that because we are selecting sources based on the existence of optical light curves, we are biased against very evolved, heavily obscured AGB stars. All of the oxygen-rich stars in Table 1 with available infrared spectra have silicate emission features or featureless mid-infrared spectra; no stars with silicate absorption features are present in this sample.

Some examples of mid- to near-infrared phase shifts are also present in Table 1 and Figure 1. In particular, for R Hor, S Pic, and R Oct, the mid-infrared maxima precede those in the near-infrared by $\sim$10 days. There are no observed offsets in the minima of any star.

4. Comparison to Theoretical Models

To date, little discussion about the origin of phase lags has appeared in the literature. Alvarez & Plez (1998) suggested that optical-to-1-micron phase lags are due to variations in the titanium oxide (TiO) and vanadium oxide (VO) absorption in a stellar spectrum, with the TiO strongly affecting broadband V measurements, and VO contributing at ≈ 1 μm. These molecules are formed in different layers of the stellar atmosphere. As the star pulsates, shock waves travel through these layers, creating and destroying these molecules at different times, causing the opacities to vary with different phases.

To further investigate the origin of phase lags, and to understand the observed differences between the lags in different types of stars, in this section we compare our results to recent theoretical models of AGB stars.

4.1. Oxygen-Rich Stars

A series of six time-resolved dynamical models for oxygen-rich stars has been produced by Bessell, Scholz, & Wood (1996) and Hofmann, Scholz, & Wood (1998), supplemented by Tej et al. (2003), Ireland, Scholz, & Wood (2004), and Ireland et al. (2004). These models include molecular opacities but not dust formation, and give reasonably good fits to the optical and near-infrared ($0.5 - 2.5$ μm) spectra of oxygen-rich Miras (Tej et al. 2003). The parameters of the six model stars in these papers are tabulated in Tej et al. (2003). They have periods from $320 - 332$ days, masses between $1 - 2$ $M_{\odot}$, luminosities of $3470 - 6310$ $L_{\odot}$, and bolometric amplitudes of $0.5 - 1.2$ magnitudes. Four are fundamental mode pulsators, while two pulsate in the first overtone.

M. Scholz (2005, private communication) kindly provided us with the theoretical spectra for these six models. We convolved these spectra with the DIRBE 1.25 μm, 2.2 μm, and 3.5 μm broadband filter response functions, as well as a standard V filter, to produce model broadband light curves. In four of the six models, clear broadband optical-near-infrared phase lags are seen, with the optical preceding the near-infrared by $\approx 0.1 - 0.2$ phase. Inspection of the model spectra shows that this lag is caused by strong TiO absorption in the optical near stellar maximum (see Figure 8 in Bessell,

Scholz, & Wood 1996). The infrared light curves tend to be more symmetric than those in the optical, which often show a more gradual decline from maximum (see, for example, S Pic in Figure 2). The infrared broadband fluxes more closely trace the bolometric luminosity of the star (Dyck, Lockwood, & Capps 1974; Blackwell et al. 1990), while the optical light curves are strongly attenuated by absorption. The TiO absorption truncates the rise in the optical light at about phase ≈ 0, before the true maximum in the near-infrared. Near-infrared VO and water absorption becomes stronger at later phases than TiO (see Figure 8 in Bessell, Scholz, & Wood 1996). Water has strong features in the $2.5 - 4$ μm range (Aringer, Kerschbaum, & Jørgensen 2002), which vary with pulsation cycle (Matsuura et al. 2002).

Interestingly, the four models with the phase lags are all fundamental mode pulsators; the two first overtone models (models E and O in Tej et al. 2003) do not show phase lags. This supports the idea that Miras are fundamental mode pulsators, while the semi-regulars without phase lags pulsate in the first overtone. Such a difference in mode has been suggested before, based on luminosity-vs-period diagrams, shock amplitudes, and light curve shapes (Hill & Willson 1979; Willson & Hill 1979; Bessell, Scholz, & Wood 1996; Willson 2000).

The two models without phase lags have the lowest bolometric amplitudes, 0.5 and 0.7 magnitudes, consistent with them being semi-regulars. Miras have larger amplitudes and longer periods than semi-regulars (Kholopov et al. 1985-1988). Semi-regulars are better fit with hydrostatic models than Miras (Loidl, Lançon, & Jørgensen 2001; Sudol et al. 2002), thus dynamical effects are more important in Miras.

Since these models do not include a complete treatment of dust, they only extend to 4 μm. They therefore cannot be used to investigate the observed mid-infrared/near-infrared phase shifts. Such offsets may be due in part to dust emission in the mid-infrared, powered by optical-UV heating. This should be investigated with more complete models including both molecular opacities as well as dust formation, coupled to a dynamical model of stellar pulsations. Including the silicate emission features would also be useful, since these contribute to the 12 μm broadband flux and are

known to vary with pulsation cycle in AGB stars (Little-Marenin, Stencel, & Staley 1996; Creech-Eakman et al. 1997; Monnier, Geballe, & Danchi 1998; Onaka, de Jong, & Yamamura 2002). As noted by Bessell, Scholz, & Wood (1996) and Ireland et al. (2004), these models also do not treat deep molecular absorption perfectly, thus the V and L (3.6 μm) band fluxes are also somewhat uncertain.

4.2. Carbon Stars

Although TiO absorption can account for the observed phase lags in oxygen-rich Miras, they cannot explain the observed phase lag in the carbon Mira V CrB. For this, carbon star models are needed. The most complete models of carbon AGB stars to date are those of S. Höfner and her collaborators (Höfner et al. 1998; Höfner 1999; Loidl et al. 1999; Höfner et al. 2003; Gautschy-Loidl et al. 2004). The latest models include time-dependent dynamics and frequency-dependent radiative transfer, as well as self-consistent time-dependent dust formation. They provide good fits to carbon star spectra from $0.5 - 5$ μm, but show some discrepancies at longer wavelengths (Gautschy-Loidl et al. 2004). The model parameters vary between luminosities of $5200 - 13,000$ L$_\odot$, stellar masses of $1 - 2$ M$_\odot$, effective temperatures of $2600 - 3400$K, periods between 148 and 525 days, amplitude velocities of $2 - 6$ km s^{-1}, and carbon-to-oxygen ratios C/O $= 1.05 - 2.0$ (Höfner et al. 2003; Gautschy-Loidl et al. 2004). These models give mass loss rates of $0 - 8 \times 10^{-6}$ M$_\odot$/yr, and bolometric amplitudes of $0.10 - 0.81$ amplitudes (Gautschy-Loidl et al. 2004).

R. Gautschy-Loidl (2005, private communication) kindly provided us with integrated broadband colors for these models. About half of these models produce broadband optical-near-infrared phase offsets, some in which the optical precedes the infrared, and some the reverse. The models with phase offsets tend to have higher luminosities, cooler temperatures, higher mass loss rates, higher bolometric amplitudes, and higher periods, but not in all cases.

The optical spectra of carbon stars are dominated by absorption from C_2 and CN, while in the near-infrared C_2H_2, HCN, C_3 and CO are present (see Loidl et al. 1999). CN and C_2 form deeper in the atmosphere than C_2H_2, C_3, and HCN (Loidl

et al. 1999), thus are affected at different times by a shock wave. In the Loidl et al. (1999) model spectra, C_2H_2 absorption is minimum near stellar maximum, while the C_2 and CN absorption is weakest ≈ 0.1 phase before C_2H_2. This is likely the cause of the observed phase lag in the Mira V CrB. This should be confirmed with time-resolved spectroscopic observations of V CrB.

According to Bergeat & Chevallier (2005), the two carbon stars in our sample, the Mira star V CrB and the semi-regular UX Dra, have bolometric luminosities of $6500L_\odot$ and $10,600L_\odot$, effective temperatures of 2090K and 3090K, and mass loss rates of 1.3×10^{-6} $M_\odot$/year and 3.7×10^{-7} $M_\odot$/year, respectively. Their periods are 358 days and 168 days, respectively (Kholopov et al. 1985-1988), and their DIRBE 2.2 μm amplitudes (which approximate the bolometric amplitudes) are 0.8 and 0.1 magnitudes, respectively. Although there are no perfect matches to these particular sets of parameters in the published models, except for the low temperature of V CrB each parameter is in the range covered by the models. The lower temperature, higher mass loss rate, and larger amplitude of V CrB compared to the UX Dra is consistent with it being more likely to have a phase lag, as observed. New models with parameters better matched to these specific stars would be helpful to compare with these light curves.

5. Conclusions

Using infrared light curves from DIRBE and optical data from the AAVSO, we have found infrared-optical phase lags in 17 stars, and no lags in 4 stars. The Mira stars all show phase lags in which the optical maximum precedes that in the near-infrared, while most of the semi-regulars show no lags. Comparison to published models shows that in the oxygen-rich Miras, the phase lags are due to strong TiO absorption in the optical near stellar maximum. Published large amplitude, fundamental mode models of oxygen-rich AGB stars show phase lags, while no lags are seen in models with small amplitude overtone mode pulsation. This is consistent with previous suggestions that Miras are fundamental mode pulsators, and semi-regulars pulsate in the overtone mode. The sole carbon Mira in the sample, V CrB, shows an optical-first lag similar to that seen in the oxygen-rich Miras; this is likely due to C_2 and CN absorption in the visible.

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Fig. 1.— Filtered DIRBE light curves for the sample stars, compared to optical light curves from the AAVSO. The stars are in R.A. order, as in Table 1.

Fig. 2.— More filtered DIRBE light curves for the sample stars, compared to optical light curves from the AAVSO.

Fig. 3.— More filtered DIRBE light curves for the sample stars, compared to optical light curves from the AAVSO. The RX Lep optical light curve is from Percy, Wilson, & Henry (2001).

Fig. 4.— More filtered DIRBE light curves for the sample stars, compared to optical light curves from the AAVSO.

Fig. 5.— More filtered DIRBE light curves for
the sample stars, compared to optical light curves
from the AAVSO. The UX Dra optical light curve
is from Buchler, Kolláth, & Cadmus (2004).

Fig. 6.— More filtered DIRBE light curves for the sample stars, compared to optical light curves from the AAVSO.

TABLE 1

DIRBE STARS WITH HIGH QUALITY OPTICAL AND INFRARED LIGHT CURVES

DIRBE NAME	NAME	Var Type	C/O Type	Period (days) (GCVS)	Period (days) (this work)	λ (μm)	Optical/IR Lag (weekly avg) (days)	(phase)	(correlation) (days)	(phase)
D00240197P3834373	R And	M	S	409	412	12	≥ 39	≥ 0.10	≥ 24	≥ 0.06
D01194198P7236407	S Cas	M	S	612	598	3.5	≥ 23	≥ 0.04	≥ 9	≥ 0.02
						4.9	≥ 25	≥ 0.04	≥ 9	≥ 0.02
						12	≥ 28	≥ 0.05	≥ 30	≥ 0.05
D02535274M4953225	R Hor	M	O	408	395	1.25	$79\pm^{6}_{5}$	$0.20\pm^{0.02}_{0.01}$	97	0.25
						2.2	$103\pm^{7}_{5}$	$0.26\pm^{0.02}_{0.01}$	82	0.21
						3.5	$79\pm^{6}_{5}$	$0.20\pm^{0.02}_{0.01}$	77	0.19
						4.9	$79\pm^{6}_{5}$	$0.20\pm^{0.02}_{0.01}$	58	0.15
						12	$19\pm^{32}_{19}$	$0.05\pm^{0.08}_{0.05}$	38	0.10
D03110304P1448000	U Ari	M	O	371	382	2.2	≥ 29	≥ 0.08	≥ 25	≥ 0.07
D03524704M4549480	U Hor	M	O	348	353	1.25	$103\pm^{18}_{19}$	$0.29\pm^{0.05}_{0.04}$	85	0.24
						2.2	$104\pm^{19}_{9}$	$0.29\pm^{0.05}_{0.03}$	90	0.25
						3.5	$104\pm^{24}_{30}$	$0.29\pm^{0.07}_{0.08}$	80	0.23
						4.9	$87\pm^{18}_{10}$	$0.25\pm^{0.05}_{0.03}$	57	0.16
D05100884M6419044	U Dor	M	O	394	423	3.5	$97\pm^{8}_{41}$	$0.23\pm^{0.01}_{0.10}$	60	0.14
						4.9	$97\pm^{5}_{58}$	$0.23\pm^{0.01}_{0.14}$	55	0.13
						12	$96\pm^{1}_{39}$	$0.23\pm^{0.01}_{0.09}$	50	0.12
						25	$45\pm^{7}_{41}$	$0.11\pm^{0.02}_{0.10}$	40	0.09
D05105724M4830253	S Pic	M	O	428	422	1.25	$80\pm^{7}_{16}$	$0.19\pm^{0.02}_{0.04}$	66	0.16
						2.2	$79\pm^{19}_{8}$	$0.19\pm^{0.05}_{0.02}$	88	0.21
						3.5	$78\pm^{8}_{18}$	$0.18\pm^{0.02}_{0.05}$	81	0.19
						4.9	$62\pm^{18}_{20}$	$0.15\pm^{0.05}_{0.05}$	51	0.12
						12	$9\pm^{39}_{15}$	$0.02\pm^{0.09}_{0.02}$	29	0.07
						25	$55\pm^{62}_{78}$	$0.13\pm^{0.15}_{0.18}$	28	0.07
D05112286M1150566	RX Lep[a]	SRb	0	60	129	2.2	$7\pm^{10}_{7}$	$0.05\pm^{0.08}_{0.05}$	4	0.03
D05260609M8623179	R Oct	M	O	405	408	1.25	$73\pm^{7}_{14}$	$0.18\pm^{0.02}_{0.03}$	52	0.13
						2.2	$69\pm^{10}_{2}$	$0.17\pm^{0.02}_{0.01}$	77	0.19
						3.5	$72\pm^{11}_{28}$	$0.18\pm^{0.03}_{0.02}$	55	0.13
						4.9	$59\pm^{10}_{30}$	$0.15\pm^{0.02}_{0.07}$	43	0.11
D07133229M4438233	L_2 Pup	SRb	0	141	139	2.2	$-6\pm8/-13\pm^{51}_{20}$	$0.04\pm0.06/-0.09\pm^{0.37}_{0.22}$	$-10/30$	$-0.07/0.22$
						3.5	$-6\pm^{10}_{7}/-9\pm^{54}_{21}$	$-0.04\pm^{0.07}_{0.05}/-0.06\pm^{0.39}_{0.15}$	$-10/35$	$-0.07/0.25$
						4.9	$-1\pm^{8}_{4}/8\pm^{51}_{20}$	$0.01\pm^{0.08}_{0.03}/0.06\pm^{0.37}_{0.14}$	$9/-30$	$0.06/-0.22$
						12	$0\pm^{9}_{5}/-53\pm^{52}_{20}$	$0.00\pm^{0.06}_{0.04}/-0.38\pm^{0.37}_{0.14}$	$-10/13$	$-0.07/0.09$
D11491178M4145272	X Cen	M	O	315	312	2.2	≥ 63	≥ 0.20	≥ 51	≥ 0.16
						3.5	≥ 71	≥ 0.23	≥ 46	≥ 0.15
D12362346P5929128	T UMa	M	O	257	259	1.25	$56\pm^{9}_{19}$	$0.22\pm^{0.03}_{0.07}$	52	0.20
						2.2	$44\pm^{8}_{18}$	$0.17\pm^{0.03}_{0.07}$	51	0.20
						3.5	$55\pm^{14}_{21}$	$0.21\pm^{0.05}_{0.08}$	50	0.19
						4.9	$40\pm^{9}_{34}$	$0.15\pm^{0.03}_{0.13}$	50	0.19
D13294277M2316514	R Hya	M	O	389	435	1.25	≥ 40	≥ 0.09	36	0.08
						2.2	≥ 43	≥ 0.10	55	0.13

TABLE 1—*Continued*

DIRBE NAME	NAME	Var Type	C/O Type	Period (days) (GCVS)	Period (days) (this work)	λ (μm)	Optical/IR Lag (weekly avg) (days)	(phase)	(correlation) (days)	(phase)
						3.5	≥46	≥0.11	58	0.13
						4.9	≥33	≥0.08	53	0.12
D14171992P6647391	U UMi	M	O	331	315	3.5	142^{+23}_{-56}	$0.45^{+0.07}_{-0.08}$	99	0.31
D14271640P0440414	RS Vir	M	O	354	360	1.25	57^{+121}_{-6}	$0.16^{+0.34}_{-0.02}$	40	0.11
						2.2	57^{+120}_{-7}	$0.16^{+0.33}_{-0.04}$	44	0.12
						3.5	57^{+119}_{-13}	$0.16^{+0.33}_{-0.04}$	48	0.13
						4.9	57^{+120}_{-14}	$0.16^{+0.33}_{-0.04}$	41	0.11
D15293454P7838003	S UMi	M	O	331	329	4.9	57^{+12}_{-34}	$0.17^{+0.04}_{-0.10}$	43	0.13
D15493131P3934178	V CrB	M	C	358	353	2.2	57^{+29}_{-47}	$0.16^{+0.08}_{-0.13}$	48	0.14
						3.5	58^{+29}_{-48}	$0.16^{+0.08}_{-0.13}$	56	0.16
						4.9	41^{+38}_{-48}	$0.12^{+0.11}_{-0.14}$	49	0.14
D16023917P4714250	X Her	SRb	O	95	106	2.2	$-7^{+7}_{-12}/-28^{+37}_{-12}$	$-0.07^{+0.07}_{-0.11}/-0.26^{+0.35}_{-0.11}$	-19	-0.18
						3.5	$1^{+29}_{-22}/-7^{+43}_{-38}$	$0.01^{+0.27}_{-0.21}/-0.07^{+0.41}_{-0.36}$	-17	-0.16
						4.9	$-1^{+17}_{-17}/-2\pm39$	$-0.01^{+0.07}_{-0.16}/-0.02\pm0.37$	-7	-0.07
D16481665P5748493	AH Dra	SRb	O	158	156	1.25	4^{+11}_{-16}	$0.03^{+0.07}_{-0.10}$	0	0.00
						2.2	4^{+13}_{-24}	$0.03^{+0.08}_{-0.15}$	-7	-0.04
						3.5	2^{+14}_{-22}	$0.01^{+0.09}_{-0.14}$	-11	-0.07
D19213546P7633345	UX Dra[b]	SRa	C	168	191	1.25	-10^{+78}_{-53}	$-0.05^{+0.41}_{-0.28}$	11	0.06
						3.5	-15^{+62}_{-45}	$0.08^{+0.32}_{-0.24}$	1	0.01
D23582487P5123190	R Cas	M	O	430	437	1.25	127^{+22}_{-115}	$0.29^{+0.05}_{-0.26}$	≥50	≥0.11
						2.2	121^{+22}_{-110}	$0.28^{+0.05}_{-0.25}$	≥92	≥0.21
						3.5	121^{+22}_{-104}	$0.28^{+0.05}_{-0.24}$	≥46	≥0.11
						4.9	17^{+107}_{-16}	$0.04^{+0.24}_{-0.04}$	≥39	≥0.09
						12	17^{+107}_{-17}	$0.04^{+0.24}_{-0.04}$	≥20	≥0.05
						25	17^{+107}_{-27}	$0.04^{+0.24}_{-0.06}$	≥18	≥0.04

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[a]Optical light curve from Percy, Wilson, & Henry (2001)

[b]Optical light curve from Buchler, Kolláth, & Cadmus (2004)

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